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TECHNICAL INNOVATION

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Atlantoaxial fusion using anterior transarticular screw fixation of C1–C2: technical innovation and biomechanical study

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Abstract This study is an attempt to describe a new technique for anterior transarticular screw fixation of the atlantoaxial joints, and to compare the stability of this construct to posterior transarticular screw fixation with and without laminar cerclage wiring. Nine human cadaveric specimens were included in this study. The C1–C2 motion segment was instrumented using either anterior transarticular screws (group 1), posterior transarticular screws alone (group 2), or posterior screws with interlaminar cerclage wires (group 3). Using an unconstrained mechanical testing machine, the specimens were tested in rotation, lateral bending, and flexion-extension using nondestructive loads of ±2 N m. The specimens were also tested in translation using nondestructive loads of ±100 N. All values for the three groups with regards to anterior-posterior displacement, rotation, and lateral bending were similar as determined using a Kruskal–Wallis rank sum test with a significance level of $p < 0.05$. The only significant difference was registered in flexion-extension where the cerclage wire added some strength to the construct. Anterior transarticular screw fixation of the atlantoaxial spine has several advantages over posterior fixation techniques, and is as stable as posterior transarticular fixation in all clinically significant planes of motion. The addition of posterior interlaminar cerclage wiring further improves resistance to flexion-extension forces. Anterior transarticular screw fixation of the atlantoaxial joint is a useful technique for achieving C1–C2 stabilization.

Keywords Atlas · Axis · Fracture · Spinal instability · Transarticular fixation

Introduction

Stability of the atlantoaxial joint can be compromised in cases of infection, trauma, tumor, congenital laxity or anomaly, degenerative disease, or inflammatory arthritis. In such cases, surgical stabilization may be necessary to prevent neurologic damage or relieve pain. C1–C2 fusion for atlantoaxial instability has historically been a difficult problem for the spine surgeon [3, 5, 7, 12, 32, 33]. The atlantoaxial joint is very mobile and accounts for 50% of the range of motion in the cervical spine in rotation [38]. Because of this, fusion rates at the C1–C2 motion segment have been lower than in the subaxial spine [5, 33].

One of the earliest types of fixation for C1–C2 fusion was described by Gallie [13]. It involved fixation of the posterior arch of C1 and the lamina or spinous process of C2 using a cerclage wire technique with onlay bone graft. Unfortunately, failure rates using this technique are unpredictable, ranging from 2% to as high as 80% [5, 6, 10–12]. A modification of this technique by Brooks has also had limited success with up to a 30% failure rate [4, 6, 14]. Another technique by Halifax using clamps with a claw-type construct has resulted in a 20% failure rate [2, 6, 35].

In 1986, Magerl developed a technique for C1–C2 fusion using transarticular screws. The screws were inserted through a posterior approach combined with a Brooks type of cerclage fixation and bone grafting of the posterior elements [23]. Several series have reported 95–100% fusion rates with his method [6, 10, 15, 36]. The success of the Magerl technique lies in the central screw positioning which provides better control of stability than the previously mentioned techniques which rely only on peripheral fixation. Posterior transarticular screws using the Magerl technique offer several advantages over those of its predecessors. They do not require immobilization in a Halo vest postoperatively, and biomechanical studies have shown this construct to be superior to Halifax, Gallie, and Brooks fixation [16, 18, 39]. Excellent results have also been obtained with the use of Magerl screws without posterior bone grafting or cerclage wiring [17, 36]. The use of transarticular screws alone avoids any complications associated with the passage of sublaminar wires. This is especially important in situations where inflammatory disease with soft tissue swelling and pannus has resulted in compromise of the spinal canal, or in the case of C1–C2 subluxation which is not completely reducible. It also avoids complications associated with graft migration, allows for laminectomy for decompression when necessary, and makes fusion possible even in the presence of defects of the posterior arch of the atlas.

Despite its success, there are complications associated with the Magerl technique [10, 15, 40]. It is a technically demanding procedure and poses risks of injury to the spinal cord and vertebral artery [23, 33]. It requires a posterior exposure which has been associated with a complication rate as high as 10% involving superficial infections and occipital nerve injury [15, 36, 40]. Some authors have described a minimally invasive technique for screw insertion, but this complicates an already technically demanding procedure, and is only possible with certain body habitus [25]. In addition, it has been found that there are situations where posterior screw insertion is not possible due to certain anatomic factors found in up to 22% of patients [22, 24, 30]. These include erosions secondary to inflammatory arthritis, a narrow pars intraarticularis measuring less than 5 mm in diameter, or a high-riding foramen transversarium that places the vertebral artery at an unacceptably high risk of injury with this type of screw insertion.

With the recent popularity of anterior surgical approaches to the cervical spine, certain centers have attempted anterior screw placement for fixation of the atlantoaxial joint using a variety of anterior and lateral approaches [17, 21, 34, 37]. The exact technique for fixation using an anterior Smith–Robinson approach has not been described. This approach offers several advantages. The surgical approach is far less traumatic and exploits a virtual space rather than dissection through muscle, therefore lowering the infection rate. It also leaves a more cosmetically acceptable scar. It should also decrease risk of vertebral artery injury as the starting point is closer to the vertebral artery foramen and therefore the path of the screw should be easier to control. In addition, the occipital condyles limit potential migration of a K-wire or placement of a long screw which would otherwise risk injuring the adjacent nervous structures. Finally, in the trauma setting position of the patient is much simpler and would be preferred in the case of an unstable cervical spine.

With this study we describe a technique for transarticular screw fixation of the atlantoaxial joint using an anterior (Smith–Robinson) approach to the cervical spine [19]. We compare the stability of this construct to other clinically successful techniques for C1–C2 fusion such as the Magerl screws with and without cerclage wires.

Materials and methods

Study design and specimen selection

Ten cervical spine specimens were harvested from routine autopsies using a technique which carefully preserved the integrity of the C1–C2 motion segment [41]. Four spines were from male donors, and three from female donors, with three unknown. The average age of the specimens was 51.7 years, ranging from 19 to 75 years. The specimens were wrapped in wet gauze, sealed in plastic bags, and stored at −20°C until testing. Any spines with relevant pathologies as seen on post mortem radiographs in two planes were excluded from the study.

The ten specimens were then divided into two equal-size test groups. Initially we had planned to use every specimen to undergo a series of three instrumentation conditions: anterior screws, posterior screws, and posterior screws with cerclage wire. Of the two testing groups, one was to start with anterior fixation, and the other with posterior fixation. As a second instrumentation condition the alternate fixation was to be used. The posterior instrumentation was tested in two different configurations: first with cerclage wire, then without a cerclage wire. But, the second instrumentation condition in four of the first five specimens had to be abandoned because of fixation failure secondary to fracture or screw cut-out. In one case we were unable to pass the cerclage wire and complete the alternate instrumentation. Because of this we decided to modify the protocol. All subsequent specimens, therefore, were only tested in the first instrumentation condition. All specimens tested for posterior fixation were tested both with and without cerclage wire.

Specimen preparation

The atlas (C1) and axis (C2) were isolated and cleaned of all muscular tissue. The transverse ligament was disrupted, but the remainder of the ligamentous and osseous structures remained intact. The specimens were then potted in polymethyl-methacrylate using a custom mold. Specimens were kept moist with saline-soaked gauze and were periodically sprayed with saline solution to prevent dessication of the tissues. Three screws were inserted into both the C1 and C2 vertebrae. They were placed in the body and posterior elements of the vertebrae to supplement the anchorage in the polymethyl-methacrylate. Care was taken to ensure that these screws would not interfere with the instrumentation. The odontoid also retained full clearance, and access to C2 for transarticular screw placement was maintained. Similarly, space was kept for the passage of cerclage wires around the posterior elements of both C1 and C2 (Fig. 1a, b).

Instrumentation technique

Magerl screws

The insertion point for the screw was on the dorsal part of the axis at the junction of the lamina and the articular mass. The wire was placed approximately 2 mm lateral to the concavity of the medial arch of the lamina, and 3 mm superior to the inferior articular process. A 1.25-mm threaded K-wire was advanced into the posteromedial surface of the isthmus, 0° in the coronal plane to avoid both the vertebral artery canal and the spinal canal. The wire was angled in the sagittal plane such that it crossed the posterior third of the atlantoaxial joint and entered the atlas in the midpoint of its articular process. The wire was advanced until it perforated the anterior cortex of the atlas. The screw length was measured and a 3.5-mm self-cutting cannulated cortical screw was inserted. A 1.5-mm cerclage wire was secured around the posterior elements of C1 and C2 as described by Brooks [4]. A 15-mm wood block was used to simulate cortical bone graft [28]. After testing this construct, the cerclage wires and "graft" were removed. For the second test, the screws were tightened and the test series was repeated.

Anterior transarticular screws

The insertion point for the screws was at the midpoint of the C2 body in the medial third of the C1–C2 articulation, just below the sulcus on the anterior body of C2. A 1.25-mm threaded K-wire was advanced into the body of C2 in a posterior and superior direction, with an angle of 20° in the coronal plane and 30° in the sagittal plane (Fig. 2a, b). It crossed the atlantoaxial joint just anterior to its midpoint. The wire was advanced until it reached the subchondral bone of the superior joint surface of the C1 massa articularis. The screw length was then measured and a 3.5-mm self-cutting cannulated cortical screw was inserted.

Mechanical testing

All specimens were tested using an 858 Mini-Bionix testing machine (MTS, Eden Prairie, MN, USA). The transducers on this machine are able to measure angular displacement in degrees with a combined accuracy and linearity <0.3% of full scale (270°). They can also measure axial compression-tension and torsion-load in N and N/m, respectively, with a combined accuracy and

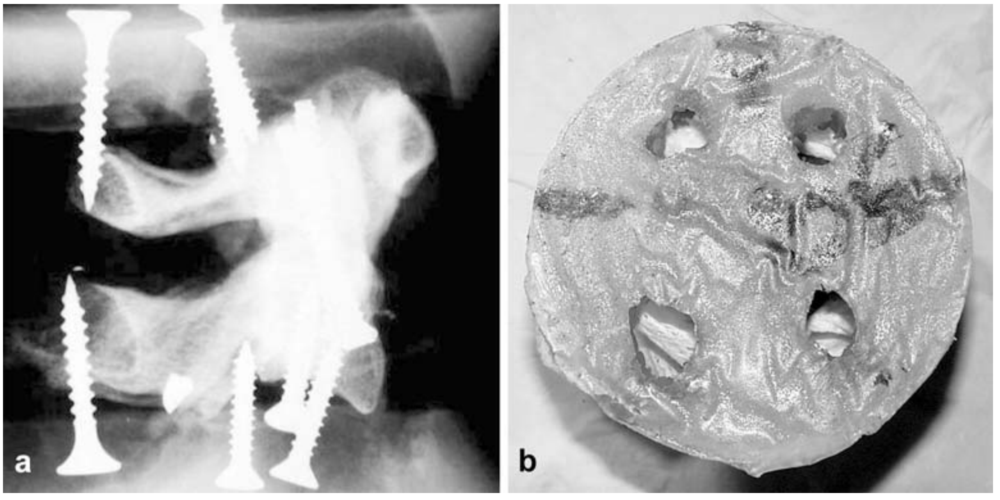

Fig. 1 C1–C2 specimen. **a** Lateral X-ray of specimen with screws placed in the body and posterior elements of the vertebrae to supplement the anchorage in the polymethyl-methacrylate. **b** View of specimen from the bottom with void for placement of transarticular screws in correct trajectory

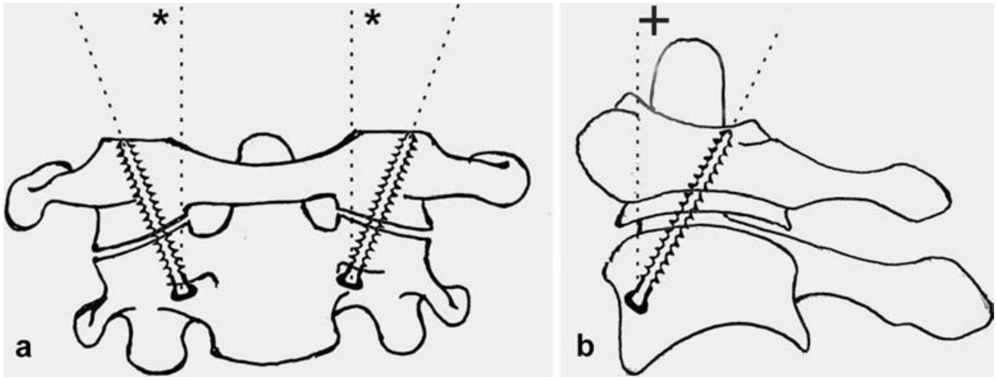

Fig. 2 Orientation of anterior transarticular screws relative to C1–C2. **a** Anterior-posterior view (*20°). **b** Lateral view ($^{+}$30°)

linearity of 0.08% of full scale (2,000 N and 100 N/m, respectively).

Load was then applied to test displacement in anterior-posterior translation, flexion-extension, left-right lateral bending, and left-right axial rotation. The specimens were tested for each instrumentation condition in this same test order.

A vertical, as well as a horizontal, mounting of the specimen was used for this test sequence (Fig. 3a, b). Initial mounting of the specimens was in a neutral position with no forces applied. The movements in the directions other than the primary loading direction were always kept unconstrained.

Each specimen was taken through two preconditioning cycles prior to making measurements on the third cycle. For anterior-posterior translation, specimens were tested from −100 N to +100 N, using a 25 N/s ramp. A 50-N preload was applied, and linear displacement was measured in millimeters. For the remainder of the tests, the specimens were taken from −2.0 N m to +2.0 N m using a 0.25 N m/s ramp. Again, a 50 N preload was applied and angular displacement was measured in degrees.

An attempt to first measure the displacement of the intact (noninstrumented) specimen as a baseline was abandoned, because the specimens were too lax. Around the zero load conditions, large and uncontrolled movements of the actuator were observed, making load controlled tests impossible without damaging the specimens.

Statistical analysis

The load–displacement curve was plotted for each specimen and each loading direction. Usually the second and third cycles were very similar. Only the third cycle was used for data analysis. Values for ranges of motion (ROM) and neutral zones (NZ) were extracted from the curves. The neutral zone is a measure of the laxity of the construct and is defined as the motion that takes place between the two vertebrae starting at the neutral position up to the point at which some resistance is offered by the joint [38]. The ROM was measured as the total amount of motion in a given plane for that particular construct. Due to the low numbers of only five data points per instrumentation condition, strictly descriptive

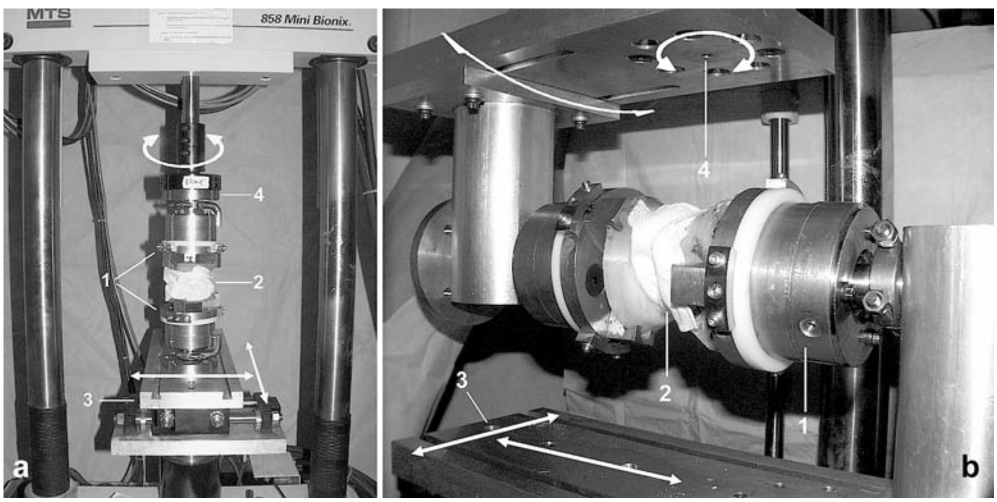

Fig. 3 Specimens mounted in testing apparatus. **a** Vertical setup: *1* Three-point clamping mechanism; *2* specimen; *3* lower platform ($X\!-\!Y$ slide); and *4* upper platform (rotates about Z). **b** Horizontal setup: *1* Three-point clamp clamping mechanism; *2* specimen; *3* lower platform ($X\!-\!Y$ slide); and *4* upper platform (swings/rotates about Z)

data representations and nonparametric tests were used. Differences between groups were analyzed using a Kruskal–Wallis rank sum test, with a significance level of $p < 0.05$.

Results

Of the five specimens tested in the posterior fixation group, one specimen had to be excluded because we were unable to pass the cerclage wire and, in addition, when testing the specimen with posterior screws alone the lower mold was torn off. All five specimens of the anterior fixation group were tested successfully.

The data for ROM and NZ are presented with median and data ranges (Table 1). Differences between instrumentation techniques were found only in the flexion-extension movements, with a significant difference ($p < 0.05$) for the ROM, and a marginally significant difference ($0.05 < p < 0.10$) for the NZ. The posterior fixation with cerclage wire appeared to be more stable than either anterior or posterior transarticular screws alone.

Discussion

The goal of surgical stabilization of a motion segment of the spine is always the same: to achieve enough immediate stability to enhance healing potential and promote bony fusion. Several surgical techniques for C1–C2 stabilization and fusion have been described in the literature [4, 13, 21, 23, 25, 36, 37]. In this study we discuss a new approach to C1–C2 stabilization using transarticular screws placed anteriorly.

We developed a unique setup for testing C1–C2 fixation constructs. Whereas former biomechanical studies on the atlantoaxial joint used specimens with intact C0–C3 motion segments [16, 20, 28], we were able to isolate the C1–C2 motion segment. Although using multisegmental specimens has the advantage of preserving ligaments crossing multiple levels, the accurate application of loads for comparison across different specimens is difficult. We think unisegmental testing has an advantage by eliminating many variables and allowing a more accurate comparison across different instrumentation groups. Our custom molds and the matching clamps allowed us to hold the atlas and axis firmly, while still permitting unrestricted segmental motion and no interference with the placement of instrumentation. Displacement measurements were taken directly from the fixation clamps, rather than with the use of an optical system with infrared or photoradiographic markers [16, 20, 28]. This is a novel method for stability testing of the cervical spine which provides reliable results with reproducible and valid data.

To minimize interspecimen variation, our initial plan was to test all specimens in an intact as well as instrumented stage, and to express the fixation strength in relation to the intact mobility. However, testing the intact specimen in any movement other than translation was not feasible given the load controlled protocol. This is because in order to isolate and mount the C1–C2 specimens we must disrupt certain structures, such as the tectorial membrane and the alar ligaments. This compromises the stability of the innate specimen, especially with regards to rotation or flexion-extension moments. We also planned to test all three instrumentation conditions on each specimen, and benefit from the increased statistical power of a paired study design. Unfortunately, after placement of one form of C1–C2 transarticular screw fixation, it was not feasible to place a second set of screws in an alternate direction through the same joint.

Table 1 Median and data ranges for range of motion and neutral zone, calculated for all instrumentation conditions and all motion directions

Instrumentation	Motion direction	n	Range of motion (degree or mm)	Neutral zones (degree or mm)
Anterior screws	Flexion-extension	5	5.41 (3.63–8.74)*	1.07 (0.76–1.59)**
	Axial rotation	5	1.67 (1.19–5.29)	0.47 (0.38–2.51)
	Side bending	5	0.97 (0.86–3.48)	0.36 (0.24–0.57)
	AP translation	5	2.06 (1.92–3.78)	0.42 (0.26–2.42)
Posterior screws	Flexion-extension	4	6.84 (4.61–12.85)*	1.36 (0.64–1.56)**
	Axial rotation	4	1.74 (1.00–3.56)	0.64 (0.11–1.56)
	Side bending	4	1.24 (1.19–6.21)	0.37 (0.06–1.12)
	AP translation	4	1.95 (1.87–2.2)	0.40 (0.36–0.45)
Posterior screws with cerclage	Flexion-extension	4	1.65 (1.11–3.75)*	0.51 (0.47–1.03)**
	Axial rotation	4	1.30 (0.86–1.87)	0.45 (0.39–0.61)
	Side bending	4	1.02 (0.94–1.07)	0.29 (0.23–0.37)
	AP translation	4	1.91 (1.75–2.48)	0.54 (0.12–0.68)

*Significant differences ($p < 0.05$)
**Marginally significant differences ($0.05 < p < 0.10$)

There were other limitations to this study. Human cadaveric cervical spine specimens are hard to obtain in large numbers, and as a result the statistical power of any study is weak. However, studies performed under similar conditions by other authors also used only five to eight specimens [8, 18, 28, 29]. Another limitation of this type of study is that it does not address fatigue of the constructs. However, for each specimen, the load–displacement curves were similar for all three cycles, with no fatigue failure using our testing protocol.

We were only able to demonstrate a significant difference in stiffness in flexion-extension moment. Under this testing condition, the Magerl screws with cerclage wires formed a significantly stiffer construct than the Magerl screws or the anterior transarticular screws alone. Previous studies have shown that the cerclage wires provide more stability in flexion-extension, while the posterior transarticular screws provide more stability in axial rotation and lateral bending [28, 39]. It is therefore no surprise that stability is increased in flexion-extension when cerclage wires are used. Clinically, however, there has not been any advantage to the use of cerclage wires with fusion rates as an outcome [17, 36]. This is likely explained by the fact that axial rotation and lateral bending have been shown to be the dominant movements of the atlantoaxial spine. C1–C2 spinal motion segment accounts for 50% of the rotation of the cervical spine, or a 47° arc to each side, but only 12% of the flexion-extension of the cervical spine, or a 20° combined flexion-extension arc [38]. Therefore only transarticular screw fixation is necessary to control the dominant movements of the atlantoaxial spine, and based on clinical results, appears sufficient to obtain fusion.

In biomechanical tests, we were unable to demonstrate any difference based on ROM and NZ measurements between the three fixation techniques when tested in translation, axial rotation, or lateral bending. We can therefore exclude a large difference in fixation strength between anterior transarticular screws and posterior transarticular screws alone.

To our knowledge, this is the first time that this method of anterior transarticular screw fixation of C1–C2 has been comprehensibly described. Prior to this study, no information was available on how this technique of C1–C2 fixation compared to the Magerl screw technique, which is the gold standard for surgical fixation of the atlantoaxial joint.

Anterior fixation techniques offer several advantages over traditional posterior approaches and would be particularly suitable in patients where posterior screw placement is not possible. This is especially true in the case of complex fracture patterns where there is an additional odontoid fracture combined with C1–C2 instability which makes a single anterior surgical approach more favorable [1, 9, 31]. Although there is no formal fusion with addition of bone graft at the anterior aspect of the C1–C2 joint, the fracture pattern, together with instrumentation crossing a relatively small joint, appears sufficient to support a successful fusion in the acute fracture setting [31]. It remains to be seen whether or not this will also hold true for atlantoaxial instability related to inflammatory or degenerative disease. Also, if decompression is required, it will not be possible through an anterior approach to the cervical spine. In this situation, a posterior approach would be favored.

Conclusion

Our biomechanical data support our clinical case experience [31], and we feel confident recommending this procedure as a surgical option for the management of atlantoaxial instability. The strength of the construct, ease of the surgical approach, and decreased risk associated with screw insertion make anterior transarticular screw fixation comparable, and in certain situations superior, to the Magerl screw technique. Anterior transarticular screw fixation of the atlantoaxial joint is therefore a very useful and effective technique for achieving C1–C2 stabilization. Further clinical study is needed to validate this technique.

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